Beyond Uncertainties in Earthquake Structural Engineering

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Beyond uncertainties in earthquake structural engineering

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Uncertainties

Ground Motion Definition

Earthquake events and realized earthquake ground motions are extremely uncertain even with the present knowledge, and it is not easy to predict forthcoming events precisely both in time and frequency (Anderson and Bertero, 1987; Takewaki et al., 1991; 2013; 2011a; Conte et al., 1992; Ariga et al., 2006; Minami et al., 2013; Çelebi et al., 2014). For example, recently reported near-field ground motions (Northridge 1994, Kobe 1995, Turkey 1999, and Chi–Chi, Taiwan 1999), the Mexico Michoacan motion 1985, and the Tohoku motion 2011, had some peculiar characteristics that could not have been predicted. It is also true that civil, mechanical, and aerospace engineering structures are often subjected to disturbances with inherent uncertainties due mainly to their "low rate of occurrence." Worst-case analysis (Drenick, 1970; Shinozuka, 1970; Takewaki, 2006/2013; Elishakoff and Ohsaki, 2010), combined with proper information based on reliable physical data, is expected to play an important role in avoiding difficulties caused by such uncertainties. Approaches based on the concept of "critical excitation" seem promising.

There are various buildings in a city (**Figure 1A**). Each building has its own natural period and its idiosyncratic structural properties. Earthquakes trigger various kinds of ground motions in the city. The relation of the building's natural period with the predominant period of the induced ground motion may lead to disastrous phenomena, as many observations from past historical earthquakes have demonstrated. Once a large earthquake occurs, some building codes are typically upgraded, but such makeshift efforts never resolve all issues and new damage problems have occurred even recently. In order to overcome this problem, a new paradigm has to be posed. In my view, the concept of "critical excitation," and structural design based upon it, could become a powerful new paradigm. Critical excitation methods were pioneered by Drenick (1970) and Shinozuka (1970). Just as the investigation of limit states of structures plays an important role in the specification of allowable response and performance levels of structures during disturbances, the clarification of critical excitations for a given (group of) structure(s) can provide structural designers with useful information for determining excitation parameters.

After Drenick and Shinozuka's pioneering work (1970), versatile researches have been developed (Iyengar and Manohar, 1985; 1987; Pirasteh et al., 1988; Srinivasan et al., 1992; Manohar and Sarkar, 1995; Pantelides and Tzan, 1996; Tzan and Pantelides, 1996; Takewaki, 2000; 2001a;b; 2008a; Abbas and Manohar, 2002; Fujita et al., 2010a; Moustafa and Takewaki, 2010a;b; Moustafa et al., 2010; Moustafa, 2011; Takewaki et al., 2012). Details of critical excitation methods are given in Takewaki (2006/2013).

In the case where influential active faults are known during the design stage of a structure (especially an important structure), the effects of these active faults should be taken into account through the concept of critical excitation. While influential active faults are not necessarily known in advance, virtual or scenario faults and their *energy* can be predefined, especially for the design of important

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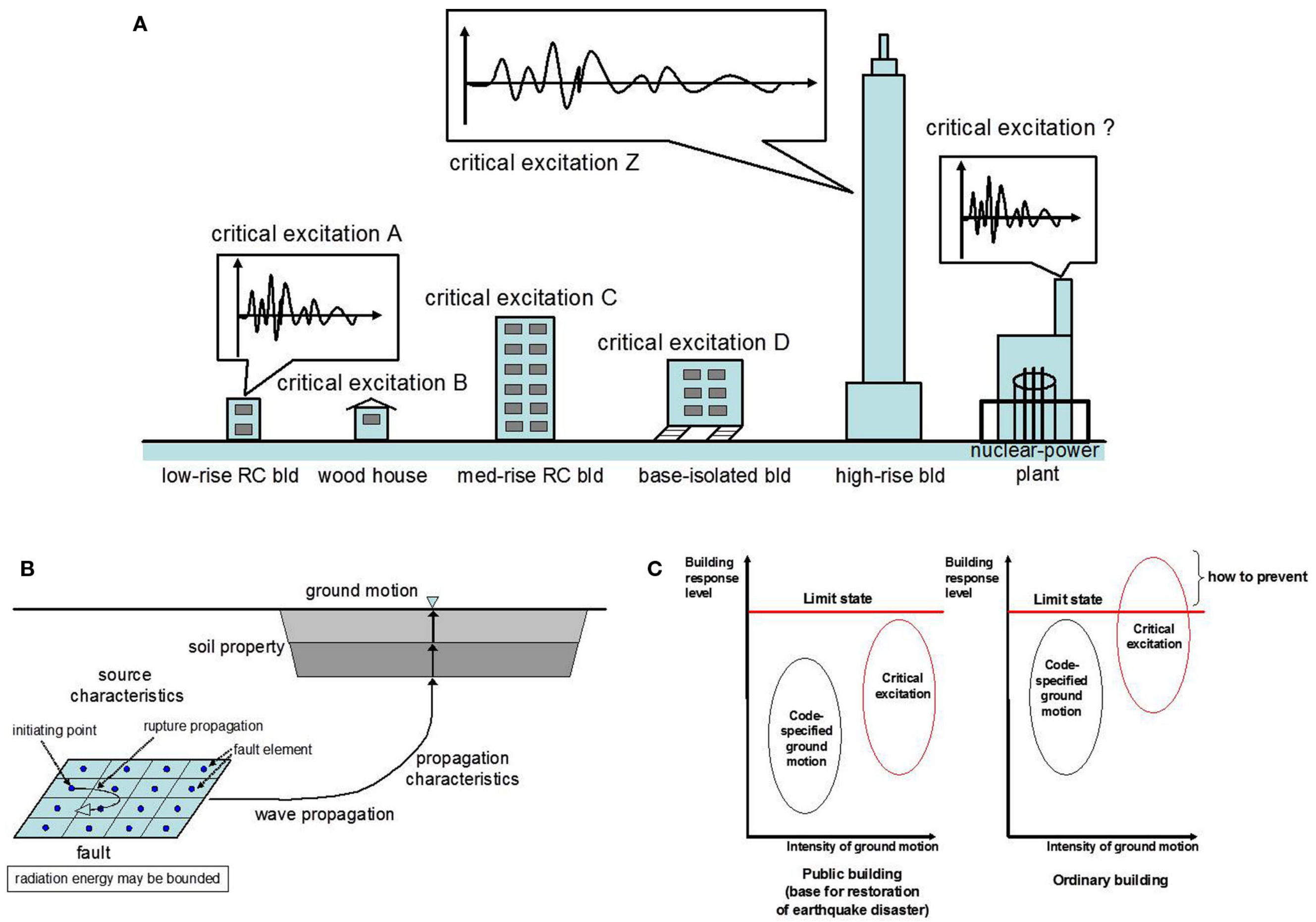

FIGURE 1 | (A) Critical excitation for each building and facility (Takewaki, 2008a), **(B)** earthquake ground motion depending on fault rupture mechanism, wave propagation and surface ground amplification, etc. (Takewaki, 2006/2013), **(C)** relation of critical excitation with code-specified ground motion in public and ordinary buildings (Takewaki, 2006/2013).

and socially influential structures. It is believed that earthquakes have an upper bound on magnitude (Strasser and Bommer, 2009). The combination of worst-case analysis (Takewaki, 2004; 2005) with appropriate specification of energy levels (Boore, 1983) derived from the analysis of various factors, e.g., the fault rupture mechanism and earthquake occurrence probability, enables more robust and reliable seismic-resistant design methods (**Figure 1B**). The appropriate setting of energy levels or information used in the worst-case analysis is important, and more research should be conducted on this subject.

In other words, the earthquake energy radiated from the fault has an upper bound (Trifunac, 2008). The problem is to find the most unfavorable ground motion for a (group of) building(s) (**Figure 1A**) (Takewaki et al., 2013). A ground motion displacement spectrum or acceleration spectrum has been proposed at the rock surface depending on the seismic moment, distance from the fault, etc. (**Figure 1B**) (Boore, 1983). Such spectra may have uncertainties. One possibility or approach is to specify the acceleration or velocity power while allowing variability of the spectrum (Takewaki and Tsujimoto, 2011; Takewaki et al., 2013).

The problem of ground motion variability is very important and difficult. Code-specified design ground motions are usually constructed by taking past observations and probabilistic insights into account. However, as stated above, uncertainties in the occurrence of earthquakes (or ground motions), fault rupture mechanisms, wave propagation mechanisms, ground properties, etc., cause much difficulty in defining reasonable design ground motions, especially for important buildings in which damage or collapse has to be avoided absolutely (see **Figure 1C**) (Anderson and Bertero, 1987; Geller et al., 1997; Stein, 2003; Takewaki, 2006/2013).

A long-period ground motion has been observed in Japan recently (Takewaki et al., 2011a). This type of ground motion is reported to require large seismic demands on such structures as high-rise buildings, base-isolated buildings, oil tanks, etc., which have a long natural period. This large seismic demand is induced by the resonance between the long-period ground motion and the long natural period of these constructed facilities. To the best of the author's knowledge, a promising approach is to shift the natural period of the building and add damping to the building by taking full advantage of technologies via seismic control (Takewaki, 2009). However, it is also understood that seismic control is still under development, while sufficient time is necessary to respond to uncertain ground motions. It is hoped that the approach of critical excitation methods (Takewaki et al., 2013) will help the development of new seismic-resistant design methods of buildings for such unpredicted or unpredictable ground motions. Critical excitation problems for fully non-stationary excitation models [see, for examples, Conte and Peng (1997), Fang and Sun (1997)] and critical excitation problems for elastic–plastic responses subjected to those excitations seem to be challenging problems.

As for response combination by multiple actions, Menun and Der Kiureghian (2000a;b) discussed the evaluation methods of envelopes for seismic response vectors. The normal stress in a structural member under combined loading of axial and bending actions may be one example. This problem is related to interval analysis (Fujita and Takewaki, 2011a;b) and its further development is warranted.

Structural Parameter Specification

Structural control with passive dampers has a successful history in mechanical and aerospace engineering, probably because these fields usually deal with predictable external loading and environments with little uncertainty. This technique is also supported by various methods of structural health monitoring (Takewaki et al., 2011b). However, in civil engineering, the situation is different (Housner, 1997; Soong and Dargush, 1997; Srinivasan and McFarland, 2000; Cheng et al., 2008; Takewaki, 2009). Building and civil structures are often subjected to severe earthquake ground motions, wind disturbances, and other external loading with large uncertainties (Takewaki, 2006/2013). It is therefore inevitable to take these uncertainties into account in structural design and its application to actual structures.

Interval analysis [see, for example, Moore (1966), Alefeld and Herzberger (1983), Qiu (2003), Chen and Wu (2004), Chen et al. (2009)] in terms of uncertain structural parameters is an effective tool for evaluating the sustainability of buildings in earthquake-prone countries. The number of combinations of uncertain structural parameters increases exponentially, but this difficulty can be overcome by introducing a sensitivity analysis or Taylor series expansion.

The critical combination of interval parameters is found by introducing an assumption of "inclusion monotony" as well as sensitivity information from Taylor series expansion. It has been demonstrated that the proposed method is useful for the development of the concept of sustainable building design under uncertain structural-parameter environments.

The concept of sustainable building design under uncertain structural-parameter environments is illustrated in **Figure 2A**. The member stiffness and strength of buildings are uncertain due to various factors resulting from randomness, material deterioration, temperature dependence, etc. The damping coefficients of structural members and/or passive dampers may also be uncertain (Takewaki and Ben-Haim, 2005). Several kinds of methods have been proposed to describe this uncertainty (Ben-Haim and Elishakoff, 1990; Ben-Haim et al., 1996; Ben-Haim, 2001/2006). The time variation of Young's modulus and damping coefficients are shown in **Figure 2A** as representative examples. Karbhari and Lee (2009) discuss the service life estimation and extension of civil engineering structures from the viewpoints of material deterioration. These member and/or damper uncertainties lead to response variability of buildings under earthquake ground motions. Efficient and reliable methods are desired for predicting the upper bound of such building response.

As stated above, interval analysis in terms of uncertain structural parameters is an effective tool for evaluating the response variability and the sustainability of buildings in earthquake-prone countries. The number of combinations of end-points of uncertain structural parameters increases exponentially, while the evaluation of the upper and lower bounds of the objective function requires elaborate manipulation. It has been shown that this difficulty can be overcome by introducing the sensitivity or Taylor series expansion analysis.

Recently, various kinds of problems with uncertain parameters have been dealt with (Kanno and Takewaki, 2006; Takewaki, 2008b; Fujita and Takewaki, 2011a;b; 2012; Takewaki and Fujita, 2014).

Unpredicted Phenomena

In recent years, unexpected phenomena in earthquake engineering have proved to be possible in a real world: for example, resonance of building vibration to ground motion in Mexico (1985) and Tohoku (2011), pulse-type ground motion in Northridge (1994) and Kobe (1995), large fault displacement in Chi–Chi (1999), giant tsunami, long-period long-duration ground motion, and soil liquefaction under smaller vibration level with longer duration in Tohoku (2011). The effects by torsional response of buildings with eccentricity and soil-structure interaction under rather soft ground may cause further unpredicted phenomena.

Because super high-rise buildings in megacities in Japan had never been shaken intensively by so-called long-period ground motions before March 11, 2011, the response of high-rise buildings to such long-period ground motions is one of the most controversial subjects and issues in the field of earthquake-resistant design in Japan (Takewaki et al., 2012; 2011a). Ground motions with large levels of velocity response spectrum in a broad frequency range including the period of 5–10 s is called the long-period ground motion. It is worth noting that most of high-rise and super-high-rise buildings in Japan have never been designed based on careful recognition of such issue. The analysis of possibility of occurrence of long-period ground motions should be investigated in more detail. The inspection of deep ground profiles may be absolutely necessary (Takewaki et al., 2013; 2012; 2011a).

Smart prediction and preparedness are extremely important and suitable for responding to such unexpected phenomena and for addressing issues related to earthquake engineering.

Strategy for Uncertainties

Worst-Case Analysis

A significance of critical excitation is supported by its broad perspective. In general, there are two classes of buildings in a

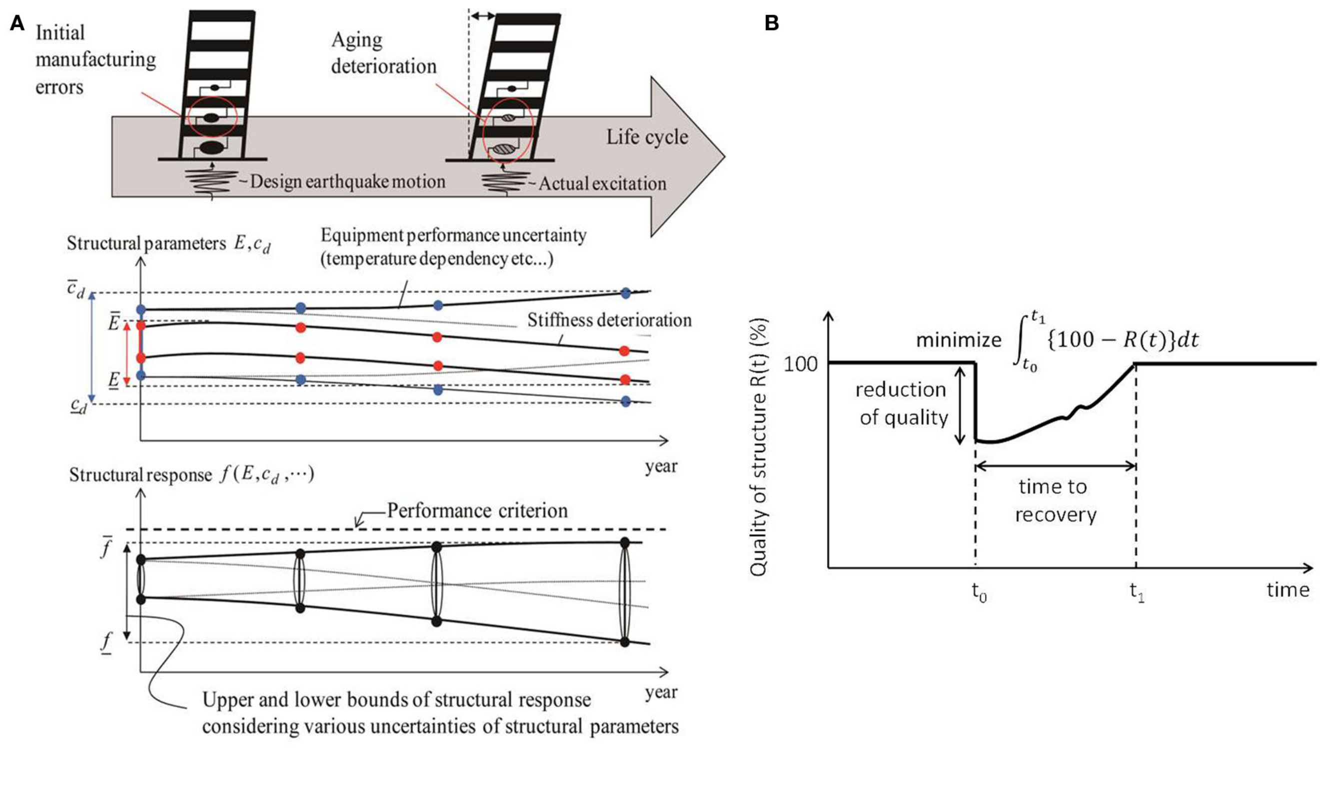

FIGURE 2 | (A) Sustainable design concept considering varied structural performance caused by various uncertainties of structural parameters (Fujita and Takewaki, 2011b), **(B)** example of earthquake resilience measure.

city. One is the important buildings, which play an important role during disastrous earthquakes. The other is ordinary buildings. The former should not be damaged during earthquakes, while some partial damage is acceptable for the latter, especially under critical excitation that is larger than code-specified design earthquakes (see **Figure 1C**). The concept of critical excitation may enable structural designers to make ordinary buildings more seismic-resistant (Takewaki, 2006/2013; Takewaki et al., 2012). The worst-case analysis is also characterized by the word of "Anti-optimization" (Elishakoff and Ohsaki, 2010). While the design of minimum cost corresponds to the design of minimum response for limited materials and a specified input, the design obtained by the anti-optimization means the design of maximum response for variable inputs.

Structural Control and Health Monitoring

While structural control is a promising and smart tool for sustainable building design (Fujita et al., 2010b), it is also true that a lot of uncertainties should be quantified for reliable implementation of these techniques (Takewaki and Ben-Haim, 2005). The sustainable building design under uncertain structural-parameter environment may be one of the most challenging issues in the building structural engineering. Even if all the design constraints are satisfied at the initial construction stage, some responses to external loadings (earthquakes, strong winds, etc.) may ultimately come to violate them over service life due to randomness, material deterioration, temperature dependence, etc. To overcome such difficulties, response evaluation methods for uncertain structural-parameter environments are needed. By predicting the response variability accurately, the elongation of service life of buildings may be possible.

Enhancement of Earthquake Resilience

Bruneau and Reinhorn (2006) discussed the earthquake resilience of building structures and infrastructures. They defined "the resilient structures" as (1) those with small collapse probability, (2) those with reduced consequences from failures in terms of lives lost, damage, and negative economic and social consequences, (3) reduced time to recovery. **Figure 2B** shows the temporal variation of performance and functionality of a structure after an earthquake. The requirements of (2) and (3) may be understood so that the minimization of the time integral of the reduction of quality, (100-Quality), corresponds to the upgrade of the resilience of the structure. They proposed four resilience measures; (1) robustness, (2) redundancy, (3) resourcefulness, (4) rapidity.

Concluding Remarks

There exist aleatory and epistemic uncertainties in the seismic structural design under earthquake ground motions. The aleatory uncertainty represents the uncertainty related to inherent randomness of a phenomenon, which cannot be reduced by the advancement of research and the epistemic uncertainty means the uncertainty concerned with knowledge which can be reduced by the development of research. While uncertainties in modeling earthquake ground motions seem to include both aleatory and epistemic uncertainties because of their extremely small probability of occurrence, uncertainties in modeling structural properties of buildings seem to contain mostly aleatory uncertainties based on the rapid advance of research in this field (although compared to the nature and level of input uncertainties). It is desired to narrow the region of epistemic uncertainties both in modeling earthquake ground motions and structural properties. Worst-case analysis, structural control and health monitoring, and introduction of the concept of earthquake resilience may be promising strategies for overcoming such unavoidable uncertainties.

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